

DMAIC-Driven Paperless Operational Reporting for Operational Efficiency and Environmental Sustainability: A Case Study at a Bottled Drinking Water Manufacturing Plant

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ABSTRACT

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Purpose— This study examines how Define-Measure-Analyze-Improve-Control (DMAIC) was used to transform manual operational reporting into paperless reporting at an Indonesian bottled drinking water manufacturing plant and evaluates the associated operational and environmental changes.

Method— An applied, participatory embedded mixed-methods single-case design combined eight Voice of Customer interviews, process observation, document review, NVivo 14 coding, root-cause analysis, 30 paired before-after observations, and post-implementation member checking. Paired differences were evaluated using Wilcoxon signed-rank and paired-samples t-tests.

Findings— After implementation, administrative workload decreased by 69.30%, reporting cycle time by 68.75%, data-retrieval time by 78.19%, and paper consumption by 99.25%. The estimated paper-related carbon footprint also declined by 99.25%. All five paired comparisons were significant at $p < 0.001$, while the documentation error rate decreased descriptively from 14.35% to 3.24%. Eight user validators reported an overall mean of 4.63/5.00.

Conclusion and Implications—DMAIC provided a traceable socio-technical architecture linking user requirements, baseline evidence, root causes, digital features, governance, and validation. Manufacturers should treat paperless reporting as process redesign supported by clear ownership, infrastructure controls, and continuing performance monitoring.

Originality/Value—The study integrates qualitative diagnosis, quantitative before-after evaluation, participatory digital implementation, environmental measurement, and Control-stage governance within one end-to-end reporting intervention, while explicitly distinguishing inferential indicators from descriptive and mathematically derived

measures.

Keywords : digital transformation; DMAIC; operational efficiency; paperless reporting; sustainable operations.



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INTRODUCTION

Manufacturing digitalisation is increasingly associated with connected equipment, real-time analytics, automated decision support, and integrated production systems. However, digital maturity is not determined only by production technology. Daily operational information may still move through handwritten forms, physical approvals, spreadsheet re-entry, and fragmented archives. These information processes affect the speed, accuracy, and traceability of operational decisions and can therefore remain a hidden source of waste in otherwise automated environments (Kraus et al., 2022; McDermott et al., 2024).

Paperless operational reporting is one practical form of process redesign. Digital forms, structured repositories, standard input fields, validation rules, and dashboards can shorten information lead time, reduce repeated transcription, strengthen traceability, and decrease paper-dependent administrative work. Yet simply converting a form into an electronic interface does not guarantee improvement. A digital process can reproduce the same duplication, delays, unclear responsibilities, and weak controls if the underlying workflow is not first understood and redesigned (Karakilic et al., 2023; Jokovic et al., 2023).

The case plant faced this challenge in production reporting. At the beginning of the study, operators, line shift leaders, and production administrators relied on more than 80 manual forms and supporting records to document output, downtime, minor stops, rejects, process parameters, line readiness, and shift handover. Data were collected, physically verified, clarified, consolidated, and re-entered into digital files before management information became available. The process generated high administrative workload, long reporting cycle time, slow historical-data retrieval, inconsistent recording, paper accumulation, and risk of damaged or lost documents.

DMAIC was selected because the plant required an evidence-based intervention rather than a technology-first implementation. The digital reporting system was not the established primary process before the study. Define was used to map the manual process and identify user requirements; Measure quantified baseline performance; Analyze identified root causes; Improve translated the evidence into a Digital Daily Reporting System; and Control established standards, monitoring, responsibilities, and reaction mechanisms. DMAIC therefore functioned as the intervention architecture, while the research design remained an embedded mixed-methods single-case study.

Four connected gaps motivate the study. First, a contextual gap remains in daily shift-based operational reporting within bottled drinking water manufacturing. Second, a

methodological gap exists because prior studies rarely show DMAIC as an end-to-end intervention integrated with Voice of Customer analysis, baseline measurement, root-cause diagnosis, digital design, control, statistical testing, and user validation in one mixed-methods case. Third, a measurement gap remains because operational efficiency and sustainability indicators are often assessed separately rather than through paired observations of workload, cycle time, retrieval time, paper use, and paper-related emissions. Fourth, an integration gap concerns the traceability of evidence from user statements to coding themes, CTQs, root causes, digital features, controls, quantitative outcomes, and member checking. In contrast to technology-centred accounts, the present study contributes a process-level explanation of how diagnostic evidence is converted into digital design and sustainment controls. Its novelty is therefore the traceable integration of qualitative diagnosis, paired operational measurement, participatory implementation, and governance within one bounded intervention; it does not rest on claiming that paperless reporting or DMAIC is new in itself.

The study therefore asks: (1) How were the Define, Measure, Analyze, Improve, and Control phases used to transform manual operational reporting into paperless reporting? (2) What changes occurred in administrative workload, reporting cycle time, and data-retrieval time after implementation? and (3) What changes occurred in paper consumption and the estimated carbon footprint associated with paper use? The contribution is a transparent chain of evidence for one information-rich case, not a universal causal model for all factories.

LITERATURE REVIEW AND HYPOTHESIS DEVELOPMENT

A. LITERATURE REVIEW

Dmaic As A Digital Process-Improvement Framework

Operations management aims to produce required outputs with appropriate quality, speed, dependability, flexibility, and cost. In operational reporting, the output is timely, reliable, and usable information. Six Sigma contributes a customer-oriented and data-based logic for reducing variation and preventing defects, while Lean focuses attention on non-value-adding activities such as waiting, repeated processing, unnecessary motion, and document inventory (Heizer et al., 2020; Ariffien et al., 2021).

DMAIC operationalises this logic in five linked phases. Define establishes the problem boundary and translates the Voice of Customer (VOC) into Critical to Quality (CTQ) requirements. Measure quantifies the current process. Analyze connects measured symptoms to root causes. Improve redesigns the process and implements solutions. Control stabilises the new method through standards, performance indicators, process ownership, audit evidence, and reaction plans. In this study, the first three phases generated the diagnosis and design requirements, Improve implemented the digital workflow, and Control supported sustainment.

This positioning is important because DMAIC is not treated as an experimental design or as a statistical proof of causality. It is a socio-technical intervention framework that links users, process steps, data structures, technology, and governance. Quality 4.0 literature supports this relationship by showing that digital validation, structured data capture, information visibility, and auditability can reinforce process consistency when they are embedded in controlled organisational routines (Jokovic et al., 2023; McDermott et al., 2024). Lean identifies administrative waste and flow interruptions; Six Sigma supplies disciplined measurement and variation-reduction logic; socio-technical systems thinking explains why process, people, technology, and governance must be redesigned together; and Quality 4.0 explains how structured digital capture, visibility, and auditability can reinforce controlled routines. DMAIC connects these perspectives sequentially without being treated as a causal theory.

Operational Efficiency In Reporting Processes

Operational efficiency in reporting refers to the ability to produce and make information available with less administrative effort and delay while maintaining process quality. The primary quantitative indicators in this study were administrative workload, reporting cycle time, and data-retrieval time. Workload represented time spent on form completion, verification, consolidation, re-entry, clarification, and archiving. Cycle time covered the period from completion of operational recording until the report was ready for use. Retrieval time operationalised information accessibility.

Data variation and documentation error rate were retained as supporting process-quality indicators. They were assessed through aggregated document audits rather than 30 equivalent paired observations and were therefore analysed descriptively, not used as inferential evidence for H1. This distinction prevents a stronger statistical claim than the data structure supports. Digital reporting can improve these measures through source-level capture, mandatory fields, dropdown categories, standard formats, automated consolidation, and centralised storage (Makhmudah et al., 2025).

Paperless Reporting And Environmental Sustainability

Sustainable operations require reductions in material use, administrative waste, and indirect environmental burden without weakening operational performance. Paper-based reporting consumes paper, toner, printing capacity, storage space, handling effort, and disposal resources. A paperless process may therefore support green operations by reducing physical documentation and the associated non-value-adding work (Costa et al., 2024; Tomaschko et al., 2024).

The environmental indicator in this study is deliberately bounded. Paper consumption was measured directly from process records, while the estimated carbon footprint was calculated using a constant conversion factor of 0.004369 kg CO₂ per sheet. Consequently, the carbon indicator is a mathematical derivative of paper use rather than independent environmental evidence. It excludes electricity, devices, servers, networks, software, maintenance, and end-of-

life impacts and should not be interpreted as a full life-cycle assessment of digital reporting. Because the same sheet-count series is multiplied by a constant factor, H3 is a transformed restatement of H2 rather than an independent test of environmental performance. It is retained only to express the paper reduction in an interpretable emissions unit, with this dependence disclosed in the hypotheses, results, and discussion.

B. HYPOTHESIS DEVELOPMENT

The qualitative analysis was guided by five propositions: paper reporting creates non-value-adding activities; digital standardisation can improve consistency and integrity; centralised access can improve information availability; paper reduction can decrease administrative waste; and faster, more structured information can support operational decision-making. The quantitative hypotheses were formulated as paired before-after differences rather than causal effects:

H1. Administrative workload, reporting cycle time, and data-retrieval time are significantly lower after implementation of Paperless Operational Reporting.

H2. Paper consumption is significantly lower after implementation of Paperless Operational Reporting.

H3. The estimated carbon footprint associated with paper consumption is significantly lower after implementation of Paperless Operational Reporting.

Table 1 Research Gaps, Study Response, and Contribution Boundary

Gap type	What prior research explains	Response and boundary of this study
Contextual	Digital reporting, paperless documentation, and process digitalisation have been studied in several sectors.	Examines shift-based daily reporting in one bottled drinking water plant; findings are context-specific.
Methodological	DMAIC and case studies are used for improvement and digitalisation.	Integrates VOC, NVivo, baseline, root causes, participatory design, Control, statistical tests, and member checking end-to-end.
Measurement	Time, quality, resource use, or sustainability are often measured separately.	Uses 30 paired observations for workload, cycle time, retrieval, paper, and paper-related CO ₂ ; error rate remains descriptive.
Integration	User needs, digital features, and controls are commonly discussed in separate evidence streams.	Traces verbatim evidence to codes, CTQs, indicators, root causes, features, controls, outcomes, and validation.

METHOD

Research Design and Context

This study used an applied and participatory embedded mixed-methods single-case design within a pragmatic paradigm. The unit of case analysis was the production-reporting process at an Indonesian bottled drinking water manufacturing plant. The researcher acted as a practitioner-researcher and participated with operators, line shift leaders, administrators, process owners, and relevant support functions in problem identification, baseline measurement, root-cause analysis, solution design, implementation, and Control. This involvement provided contextual access but also created a risk of confirmation bias, which was addressed through triangulation, audit trails, explicit indicator classification, statistical testing, presentation of implementation constraints, and member checking.

Population, Participants, and Data Collection

The accessible process population comprised 40 employees directly involved in recording, verification, consolidation, and use of operational reports: 24 production operators, 12 supervisors or line shift leaders, and four production-data or performance personnel. Eight informants were selected purposively for qualitative analysis: three operators, three line shift leaders, and two administrators. The quantitative units were not these respondents but 30 paired daily process observations collected under equivalent definitions, units, process scope, and three-shift operating patterns before and after implementation. Accordingly, qualitative claims refer to the experiences of the eight informants, whereas inferential results refer to the 30 matched process days. No employee-level statistical generalisation is made from the process observations.

Qualitative data were collected through semi-structured VOC interviews, non-participant process observation, document review, and focused technical discussions. Interviews were transcribed and analysed in NVivo 14 through open coding, axial coding, selective coding, hierarchy analysis, and matrix coding queries. After implementation, the same eight experienced users completed member checking through ten five-point Likert statements, an overall confirmation question, and open comments on benefits and remaining constraints. Coding began deductively from reporting-process concerns and remained open to inductive child codes emerging from participant statements. A codebook and decision trail linked quotations, codes, categories, CTQs, root causes, and system requirements. Triangulation across interviews, observation, documents, and technical discussions, together with member checking and retention of disconfirming implementation comments, supported credibility and confirmability.

Measures and Data Sources

The primary paired indicators were administrative workload (minutes/day), reporting cycle time (minutes/shift), data-retrieval time (minutes/case), paper consumption (sheets/day), and estimated paper-related carbon footprint (kg CO₂/day). The carbon

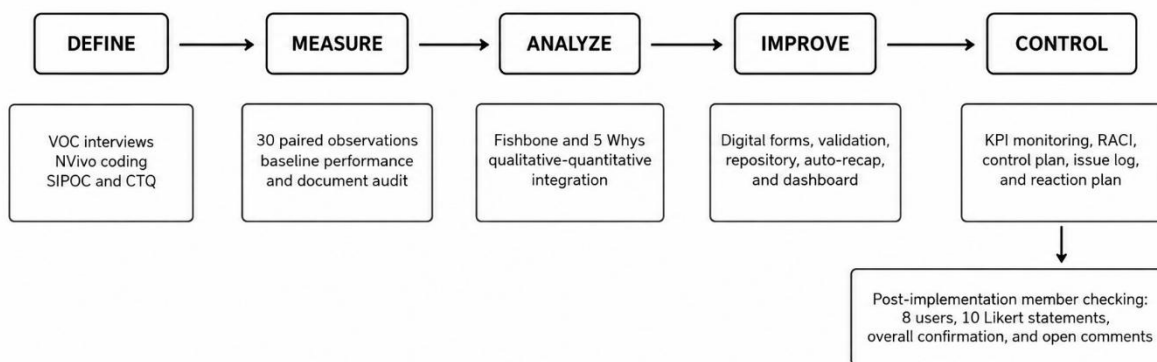
estimate used paper consumption multiplied by 0.004369 kg CO₂ per sheet. Documentation error rate and data variation were analysed descriptively because the audit results were aggregated rather than arranged as equivalent daily pairs. Estimated paper and printer cost was treated as an additional economic indication, not a complete digital-system cost analysis. Before and after observations used the same indicator definitions, units, reporting scope, and three-shift structure. Workload covered form completion, checking, clarification, consolidation, re-entry, and archiving; cycle time ran from completion of operational recording to report readiness; retrieval time ran from a data request to successful access to the required historical record.

Data Analysis and DMAIC Procedure

Analysis followed the DMAIC sequence shown in Fig. 1. Shapiro-Wilk tests were applied to paired differences. Non-normal differences were tested with the Wilcoxon signed-rank test and reported with effect size $r = |Z|/\sqrt{N}$; normally distributed differences were tested with paired-samples t-tests, 95% confidence intervals, and Cohen's $d_z = t/\sqrt{n}$. Significance was set at 0.05. Because the study had no randomisation or comparison group, results are interpreted as changes observed after implementation, not proof that every change was caused exclusively by the digital system. Each inferential test used the paired day as the analytical unit. Distributional assessment was performed on within-pair differences rather than on the separate before and after series. Effect sizes were interpreted alongside p values and confidence intervals because statistical significance alone does not establish operational importance.

Participatory embedded mixed-methods single-case study

Practitioner-researcher + users + process owners



Qualitative evidence explains the problem and mechanism; paired quantitative evidence evaluates observed change.

Figure 1 Participatory Embedded Mixed-Methods Single-Case Design Within the DMAIC Intervention Cycle

Table 2 Research Evidence and Analytical Role Across the Intervention

Stage	Evidence and tools	Primary analytical output
Define	SIPOC, eight VOC interviews, observation, NVivo 14 coding	Five user themes, CTQs, and digital requirements
Measure	Thirty-day equivalent process observations and document audits	Baseline workload, cycle time, retrieval, errors, paper, cost, and CO ₂
Analyze	Integrated evidence, contribution analysis, fishbone, and 5 Whys	Root causes and improvement priorities
Improve	Participatory digital forms, standard fields, validation, repository, auto-recap, dashboard	Digital Daily Reporting System and post-implementation measures
Control	KPI targets, control plan, evidence checks, issue log, and RACI	Standards, ownership, reaction mechanisms, and sustainment
Validation	Ten Likert statements, overall confirmation, and open comments from eight users	Member checking, practical meaning, and remaining constraints

Note. Processed research data (2026).

Ethical Considerations

The study was conducted as an organizational process-improvement case study with permission from the participating organization. Participation in interviews and post-implementation validation was voluntary, and participants were informed about the study purpose and the use of anonymized evidence. The plant identity, exact location, and personally identifiable information were withheld. Formal institutional ethics approval or exemption details were not included in the source documentation supplied for this manuscript.

RESULTS AND DISCUSSION

A. RESULTS

Define: User Voice And Critical Requirements

The SIPOC analysis showed that operational data originated from operators, production equipment, counters, and manual production documents. The process comprised recording, collection, physical verification, clarification, consolidation, re-entry, distribution, and archiving. The main customers were line shift leaders, production administrators, performance personnel, production management, and other functions requiring operational information. The mapping exposed repeated transcription, movement of physical documents, delayed readiness for review, and dependence on dispersed archives.

NVivo analysis generated 20 child codes that were consolidated into five core themes. Administrative Efficiency covered manual data entry, workload, approval, and reporting delay. Data Quality included incomplete data, inconsistent recording, human error, clarification, and validation. Information Accessibility covered difficult retrieval and delayed availability. Paper-Based Reporting included paper accumulation, document damage or loss, and complex physical workflow. Digital Reporting Expectations included integration, dropdown selection, ease of use, faster reporting, operational fit, and user adaptation.

The five themes were translated into CTQs: administrative efficiency, data accuracy, information accessibility, paper usage, and digital reporting expectations. The first four informed baseline indicators. Digital expectations were used as design requirements for Improve because no central digital platform existed at baseline. This traceability from verbatim statements to codes, themes, CTQs, measures, and design features was the central integration mechanism of the study.

Measure: Thirty-Day Baseline

The 30-day baseline demonstrated that the issues described by users were measurable process characteristics. Administrative workload totalled 11,400 minutes, or 190 hours, with an average of 380 minutes per day. Reporting cycle time averaged 80 minutes per shift, and data retrieval averaged 9.63 minutes per case. These measurements established a consistent comparison point for the same operational scope after implementation.

An audit of 1,080 documents identified 155 issues, resulting in a 14.35% documentation error rate. The main categories were non-standard formats, incomplete data, illegible writing, incorrect figures, and mismatch across records. Because the audit evidence was aggregated rather than structured into 30 equivalent daily pairs, it was used as descriptive support for data-quality interpretation rather than as an inferential component of H1.

Production reporting consumed 11,951 sheets over 30 days, equivalent to 398.37 sheets per day. Using the defined conversion factor, this corresponded to an estimated 52.21 kg CO₂ and paper-and-printer expenditure of IDR 3,488,258 during the period. The cost estimate did not include development, devices, connectivity, licences, maintenance, or digital support and therefore represents only the avoided document-related component.

Table 3 Baseline and Post-Implementation Performance

Indicator	Before implementation	After implementation	Reduction
Administrative workload	190.00 h/30 days	58.33 h/30 days	69.30%
Reporting cycle time	80.00 min/shift	25.00 min/shift	68.75%
Documentation error rate*	14.35%	3.24%	77.42%

Indicator	Before implementation	After implementation	Reduction
Data-retrieval time	9.63 min/case	2.10 min/case	78.19%
Paper consumption	11,951 sheets/30 days	90 sheets/30 days	99.25%
Estimated paper-related CO ₂ †	52.21 kg/30 days	0.39 kg/30 days	99.25%
Estimated paper and printer cost‡	IDR 3,488,258/30 days	IDR 26,269/30 days	99.25%

*Note. Processed research data (2026). *Descriptive audit indicator; †derived directly from paper consumption; ‡document-related cost only.*

Analyze: Root Causes Of Reporting Inefficiency

The integrated analysis showed that the problem was systemic rather than attributable to individual carelessness. Fishbone analysis grouped causes under people, methods, technology, materials, measurement, and work environment. The largest baseline contributions came from repeated consolidation and re-entry, manual form completion, physical verification, and searching or handling archives. Qualitative themes explained why these time and material burdens occurred.

The 5 Whys analysis identified seven principal root causes: paper-based source capture; repeated entry from paper to digital files; sequential recapitulation; manual validation after document collection; non-standard input formats; the absence of a centralised repository; and dependence on physical supporting archives. These causes established the functional requirements for digital forms, structured categories, validation rules, integrated storage, automated consolidation, dashboards, and controlled residual paper use.

Improve: Implementation Of The Digital Daily Reporting System

The Improve phase translated each verified root cause into a process and technology response. Paper forms were replaced by digital shift reports; repeated entry was reduced through single-source capture and automated consolidation; mandatory fields, dropdown selections, and validation rules standardised input; a central repository improved traceability; and dashboards provided structured access for monitoring and daily review. The system was developed and implemented through participatory technical discussions rather than as an individual product of the researcher.

The redesigned workflow changed both the medium and the sequence of work. Previously, operational events were recorded on paper, documents were collected and signed, incomplete entries were clarified, and data were re-entered before a usable report existed. After implementation, users recorded data at source, supervisors validated digital entries, and the same structured data fed consolidation, retrieval, and dashboard functions. The redesign directly addressed the root causes rather than merely reproducing the paper form on screen.

After implementation, administrative workload decreased to 58.33 hours per 30 days, reporting cycle time to 25 minutes per shift, and retrieval time to 2.10 minutes per case. The supporting documentation error rate decreased descriptively from 14.35% to 3.24%. Paper consumption decreased to 90 sheets and the estimated paper-related carbon footprint to 0.39 kg CO₂ per 30 days. Table 3 summarises the observed changes. Implementation fidelity was checked through completion evidence, supervisor validation, issue logs, and routine dashboard use. No major change to reporting scope or shift structure was recorded during the comparison window; nevertheless, learning, managerial attention, production variation, or other concurrent influences cannot be completely excluded.

Table 4 Translation of Root Causes Into Digital Improvement Features

Verified root cause	Digital process response	CTQ affected
Paper-based source capture	Digital shift reporting and electronic operational records	Administrative efficiency; paper usage
Repeated entry and sequential recapitulation	Single-source input, auto-recap, and reporting dashboard	Administrative efficiency
Manual validation after form collection	Mandatory fields and digital validation workflow	Data accuracy
Non-standard recording formats	Dropdown selections and standard data categories	Data accuracy
Fragmented physical and digital archives	Centralised repository with structured identifiers	Information accessibility
Delayed readiness for daily review	Near-real-time report and dashboard availability	Efficiency; accessibility
Physical supporting archives	Electronic storage and controlled residual paper use	Paper usage

source: Processed research data (2026).

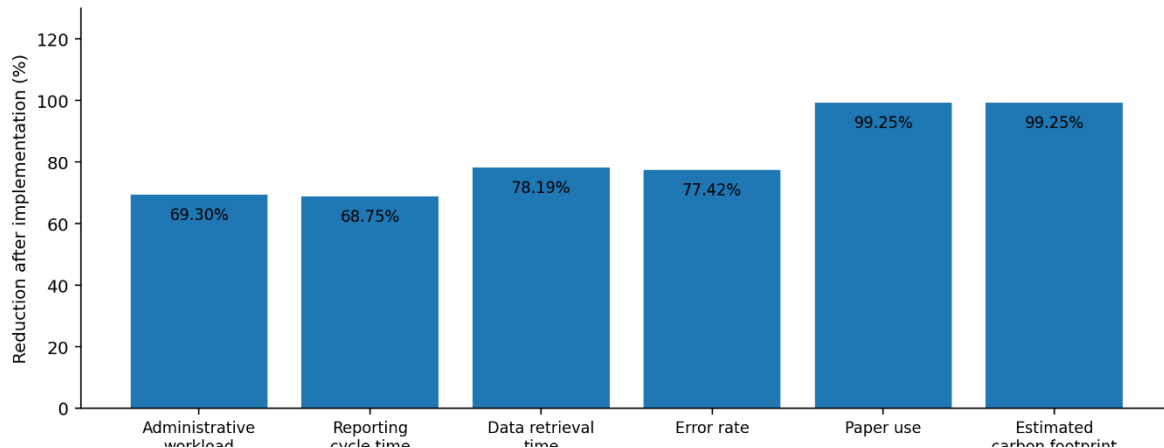


Figure 2 Reduction in Reporting-Process Indicators After Implementation

Control: Standardisation, Ownership, RACI, And Sustainment

The Control phase converted the improved workflow into an organisational routine through standard procedures, monitoring targets, evidence checks, reaction plans, and a RACI matrix. Operators were responsible for timely digital input; line shift leaders verified completeness and operational validity; administrators and performance personnel monitored consolidation, dashboard availability, and issue logs; system owners addressed technical problems; and management reviewed adherence and performance. The RACI arrangement assigned operators responsibility for source entry, line shift leaders accountability for validation, production-data personnel responsibility for master-data and consolidation controls, and process owners accountability for escalation and corrective action. Trigger breaches required issue logging, cause review, assigned action, due date, and effectiveness verification.

Control targets were set at no more than 65 administrative hours per 30 days, 30 minutes per shift for reporting cycle time, a 5% documentation error rate, three minutes per retrieval case, and 90 paper sheets per 30 days. Control evidence covered input logs, completeness checks, dashboard availability, residual paper, device and network issues, user reminders, and escalation records. These mechanisms were intended to prevent a return to dual paper-digital processing.

Statistical Hypothesis Testing

Shapiro-Wilk testing showed that paired administrative-workload differences were non-normal ($p = 0.001$), whereas cycle-time, retrieval-time, paper-use, and carbon-footprint differences met the normality assumption. The Wilcoxon test for workload

showed 30 negative ranks, no positive ranks or ties, $Z = -4.784$, $p < 0.001$, and $r = 0.873$, indicating a large standardised change.

Paired-samples t-tests also showed statistically significant reductions. Reporting cycle time decreased by 55.00 minutes, 95% CI [54.17, 55.83], $t(29) = 135.189$, $p < 0.001$, $dz = 24.682$. Retrieval time decreased by 7.53 minutes, 95% CI [7.08, 7.98], $t(29) = 34.401$, $p < 0.001$, $dz = 6.281$. Paper consumption decreased by 395.37 sheets/day, 95% CI [392.65, 398.08], $t(29) = 297.847$, $p < 0.001$, $dz = 54.379$. The carbon estimate decreased by 1.727 kg CO₂/day, 95% CI [1.715, 1.739], with the same t and dz because it is a constant mathematical transformation of paper use. The very large dz values reflect highly consistent paired differences in this tightly specified process and should not be generalised as universal effect magnitudes.

Table 5 Summary of Paired Statistical Tests and Effect Sizes

Indicator	Test	Observed reduction (95% CI)	Statistic and p	Effect size	Decision
Administrative workload	Wilcoxon	263.33 min/day	$Z = -4.784$; $p < 0.001$	$r = 0.873$; large	H1 supported
Reporting cycle time	Paired t	55.00 min [54.17, 55.83]	$t(29) = 135.189$; $p < 0.001$	$dz = 24.682$; large	H1 supported
Data-retrieval time	Paired t	7.53 min [7.08, 7.98]	$t(29) = 34.401$; $p < 0.001$	$dz = 6.281$; large	H1 supported
Paper consumption	Paired t	395.37 sheets/day [392.65, 398.08]	$t(29) = 297.847$; $p < 0.001$	$dz = 54.379$; large	H2 supported
Estimated carbon footprint†	Paired t	1.727 kg/day [1.715, 1.739]	$t(29) = 297.847$; $p < 0.001$	$dz = 54.379$; large	H3 supported

Note. Processed research data (2026). †The carbon indicator is a constant transformation of paper consumption.

Post-Implementation User Validation

Member checking was conducted with the same eight users who had experienced both the manual and digital processes. Across ten structured statements, the overall mean was 4.63/5.00, and all eight validators confirmed that the research findings were consistent with their actual experience. The strongest ratings concerned reporting speed and data quality, while infrastructure support received the lowest, although still strongly positive, mean.

Open comments confirmed practical benefits such as reduced re-entry, faster access, more consistent categories, and lower dependence on paper. They also identified a short adaptation period, occasional loading delays, network and battery readiness, screen-use constraints in wet conditions, and the need to remind users to complete digital submission. Validation therefore strengthened credibility while also revealing implementation risks that required continued Control.

Table 6 Post-Implementation User Validation

Validated aspect	Mean (/5)	Interpretation from user evidence
Administrative workload	4.75	Less manual recording, re-entry, and recapitulation
Reporting speed	4.88	Reports available without waiting for all paper forms
Information accessibility	4.63	Historical data and performance graphs retrieved directly
Data quality and consistency	4.88	More uniform categories and fewer clarification needs
Ease of use and adaptation	4.56	Usable after a short role-specific adjustment period
Paper reduction	4.75	Lower dependence on forms exposed to dirt or water
Device and network support	4.25	Adequate, but connectivity and device readiness still require control
Overall benefit	4.25	All eight users fully confirmed the study findings
Overall mean	4.63	Very strong post-implementation confirmation

Note. Post-implementation member checking; processed research data (2026).

B. DISCUSSION

Dmaic As An Architecture For Digital Process Change

The findings show that DMAIC provided more than a sequence for measuring improvement. It created a traceable intervention architecture linking user experience, process mapping, baseline evidence, root-cause diagnosis, digital design, implementation, governance, and validation. Define prevented the solution from being based solely on technical assumptions. Measure quantified the operational and material burden. Analyze clarified the mechanisms producing the burden. Improve translated verified causes into features, and Control assigned ownership and reaction mechanisms.

This interpretation extends DMAIC from conventional defect reduction to information-flow redesign and participatory digital change. It is consistent with studies applying DMAIC to paperless production, digitalisation, quality improvement, and sustainability (Al Meanazel & Almotari, 2025; Ramires & Sampaio, 2020; Rodriguez et al., 2022). The contribution is not the claim that DMAIC or digital reporting is new, but the end-to-end evidence chain connecting VOC, CTQs, indicators, root causes, features, controls, statistical results, and user confirmation.

Operational Efficiency And Data Quality

The reductions in workload, cycle time, and retrieval time are consistent with the removal of repeated transcription, physical collection, sequential consolidation, and archive searching. Operators could devote more attention to line conditions, supervisors received information earlier, and administrators performed less re-entry and clarification. The fact that all 30

workload pairs decreased and that the time-based indicators had narrow confidence intervals indicates a highly consistent change within the observed process.

Retrieval-time reduction is particularly relevant to operational control because supervisors and managers require historical data for downtime analysis, quality investigation, shift comparison, and daily review. Centralised storage and structured identifiers reduced dependence on physical archive location and individual memory. Nevertheless, faster availability does not automatically guarantee better decisions; data governance, interpretation capability, and disciplined use remain necessary.

The error rate was not included in inferential testing, but its descriptive decline from 14.35% to 3.24% supports the mechanism of mandatory fields, standard categories, and digital validation. This evidence should remain subordinate to its data structure. It indicates an improvement in audited documentation quality but does not justify a paired statistical claim comparable to the three primary efficiency indicators.

Sustainability And Green Operations

The 99.25% reduction in paper consumption shows that a supporting information process can contribute materially to green operations. The operational benefit extends beyond sheets avoided because the digital workflow also reduced printing, physical handling, storage, archive retrieval, and disposal activities. The result supports research linking Lean digitalisation with resource efficiency and reduced administrative waste (Costa et al., 2024; Tomaschko et al., 2024).

The carbon result requires a narrower interpretation. Because the estimate was calculated directly from paper consumption using a fixed conversion factor, H3 is not independent of H2 and the identical t statistic and effect size are mathematically expected. The result represents avoided paper-related emissions within the selected boundary, not the net environmental impact of the digital system. Future evaluation should incorporate device manufacture, electricity, connectivity, cloud or server use, maintenance, and end-of-life impacts through life-cycle assessment.

Integration Of Qualitative And Quantitative Evidence

The embedded mixed-methods design strengthened the explanatory value of the case. Qualitative evidence identified administrative burden, recording inconsistency, retrieval difficulty, paper dependence, and desired digital features. Quantitative baseline data established magnitude. Root-cause tools linked symptoms to mechanisms. Paired testing evaluated the direction, size, and consistency of observed changes. Control evidence showed how the new process was institutionalised, while member checking assessed whether the measured results matched user experience.

This integration reduces reliance on either perceptions or decontextualised performance figures. User narratives alone would not demonstrate statistically significant before-after

differences, while statistics alone would not explain why the process changed or how the digital features addressed operational needs. The joint interpretation nevertheless remains bounded by the absence of a comparison group, possible concurrent influences, the researcher's organisational involvement, and the 30-day evaluation horizon.

User Validation, Implementation Risks, And Interpretive Boundaries

Post-implementation validation provided convergent but not population-level evidence. The eight users produced an overall mean of 4.63/5.00 and all confirmed that the findings reflected their actual experience. Reporting speed and data quality received the highest mean scores (4.88), followed by workload and paper reduction (4.75), information accessibility (4.63), and ease of use and adaptation (4.56). Infrastructure support and overall benefit each scored 4.25, indicating strong confirmation while also identifying room for improvement. These ratings were used to assess experiential agreement with the interpreted changes, not as an independent effectiveness test or a representative employee survey. The open comments were analysed alongside the scores so that infrastructure and adaptation concerns were not obscured by the favourable mean values.

Open comments revealed practical constraints that should not be hidden by the positive averages. Users required brief adaptation to the interface, dashboard graphs, and monthly-data extraction. Occasional loading delays, network stability, device battery, screen use in wet working conditions, and reminders to complete digital submission remained relevant. Control should therefore cover user coaching, device readiness, network availability, access rights, master-data quality, audit trails, backup, issue logging, and process ownership. These constraints also reinforce the need for cautious causal interpretation.

Theoretical And Practical Implications

Theoretically, the study contributes to the intersection of Lean Six Sigma, digital transformation, Quality 4.0, and sustainable operations by positioning DMAIC as a traceable socio-technical intervention framework. It also demonstrates the analytical importance of separating inferential indicators from descriptive support and of treating paper-derived carbon estimates as dependent rather than independent environmental evidence. More specifically, it extends process-improvement research by showing that DMAIC can serve as an evidence-integration architecture: user voice defines value, measurement establishes the baseline, diagnosis identifies mechanisms, digital design addresses verified causes, and Control embeds accountability. The contribution is analytical transferability of this chain, not statistical generalisability of the observed percentage reductions.

Practically, factories should avoid treating paperless reporting as an isolated application project. Process boundaries, user roles, baseline definitions, error mechanisms, retrieval requirements, residual-paper exceptions, infrastructure, access control, master data, and ownership should be designed together. Adaptation to another location should be based on

local VOC, baseline, digital readiness, competencies, and governance rather than assumed replication of the observed results.

CONCLUSION

This study shows how DMAIC can be used as an intervention and process-improvement framework to transform fragmented paper-based reporting into a controlled digital workflow. Define identified five user-derived themes and CTQs; Measure quantified baseline burdens; Analyze verified systemic root causes; Improve translated them into digital features and a redesigned workflow; and Control established standards, targets, ownership, evidence, and reaction mechanisms.

Substantial changes were observed after implementation. Administrative workload decreased by 69.30%, reporting cycle time by 68.75%, and data-retrieval time by 78.19%. Paper consumption and the estimated paper-related carbon footprint each decreased by 99.25%. All five paired comparisons yielded $p < 0.001$, and the reported effect sizes were large. Documentation error rate also decreased descriptively from 14.35% to 3.24%. User validation produced an overall mean of 4.63/5.00 and confirmed alignment between operational indicators and lived experience.

The plant should maintain digital reporting as the official process, continue periodic review of workload, cycle time, retrieval time, documentation quality, residual paper, infrastructure availability, and issue logs, and preserve clear RACI ownership. Replication in other locations should begin with new VOC analysis, baseline measurement, infrastructure and competency assessment, local governance design, and controlled piloting rather than direct copying of the solution or expected percentage reductions.

The conclusions are limited to one factory, one production-reporting process, 30 paired observations, and eight user validators. The before-after design lacks randomisation and a comparison group, so the changes cannot be attributed exclusively to the digital system. The practitioner-researcher position may introduce bias despite triangulation and audit controls. The carbon estimate is derived from paper use and does not represent a complete environmental life-cycle assessment. Longer, multi-site, comparative studies should evaluate performance stability, broader user groups, full digital costs, decision quality, cybersecurity, and net environmental impact. Future studies should use interrupted time-series, matched-site, stepped-wedge, or controlled multi-site designs where feasible; pre-register indicator definitions; extend follow-up periods; assess implementation fidelity and decision quality; and conduct full life-cycle and total-cost assessments that include devices, electricity, connectivity, servers, maintenance, cybersecurity, and end-of-life impacts.

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DECLARATION ON THE USE OF AI-ASSISTED TECHNOLOGIES

OpenAI ChatGPT was used to assist with manuscript formatting, structural organization, and language presentation. The authors reviewed and verified the manuscript and remain responsible for all text, data, citations, figures, interpretations, and analytical outputs.

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